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Numerical simulations of the unsteady aerodynamics of a floating vertical axis wind turbine in surge motion

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ABSTRACT

When offshore floating vertical axis wind turbines (OF-VAWTs) face the ocean waves and wind loads under normal operation conditions, they have six-degrees of freedom (6-DOF) movement. Each of the 6-DOF movements will influence the aerodynamic performance of the OF-VAWTs in turn. In view of this, the present paper uses the computational fluid dynamics (CFD) method and the Improved Delayed Detached Eddy Simulation (IDDES) to investigate the aerodynamics of an OF-VAWT in periodic surge motion. The overset mesh technique is employed to simulate the rotor's surge motion. In order to verify the present CFD model, the power coefficients of a bottom-fixed VAWT at different tip speed ratios are compared between the experiments and the simulations. By contrast with the non-surge motion, the aerodynamic forces (torque, tangential force, normal force and pressure) and vortex structures of an OF-VAWT are analyzed. Subsequently, the unsteady aerodynamic performance of an OF-VAWT in different amplitudes and periods of surge motion is investigated. It is shown that the surge motion can widen the variation ranges of the aerodynamics forces, and change the flow field around the rotor. The smaller surging amplitude and larger surging period are proposed as they can reduce the variation ranges of the aerodynamics forces, and then keep the floating wind turbines more steady. In addition, the durability and power output of the wind turbines will be improved in surge motion with smaller amplitude and larger period.

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1. Introduction

With the increasing depletion of land resources, offshore wind turbines will be the main driver of wind energy technology in the future [1]. Meanwhile, wind turbines installed in the sea can achieve the wind energy which has a larger velocity and a weaker turbulence [2]. Therefore, a series of publications from Esteban et al. have shown that the Offshore Wind Farms will face many integral problems, such as environment, technology [3,4], and they also gave the methodology for the design of offshore wind farms [5]. As the components of the offshore wind farms, offshore wind turbines can be classified into two main types based on the foundation form: offshore bottom-mounted wind turbines and offshore floating wind turbines [6]. Therein, offshore floating vertical axis wind turbines (OF-VAWTs) are attracting a growing amount of attention due to the several advantages as follows [7]:

(1) VAWTs can receive wind power from omni-directions, thus there is no need for the configuration of yaw devices;
(2) The manufacturing process of OF-VAWT blades is simpler than those of offshore horizontal axis wind turbine. The lifespans are longer for OF-VAWTs;
(3) The installation and maintenance costs of OF-VAWTs are lower;
(4) OF-VAWTs cause fewer aerodynamic noise problems.

As a kind of support structure for the floating wind turbines, platforms include three main types: tension leg platforms, semi-submersible platforms and spar platforms [8]. Each kind of platform has its own unique hydrodynamic characteristics. Although the platforms of OF-VAWTs are connected to the seabed through the cables, they may produce excessive six-degrees of freedom (6-

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DOF) movement under the combined effect of wind and wave loads [9]. Meanwhile, the 6-DOF motions may affect the aerodynamics of the rotor due to the relative velocity and the skew angles [10]. Hence, understanding the impact of a certain motion on the aerodynamic performance of the wind turbine is beneficial to the platform design and the rotor optimization. There were some publications concerning the aerodynamics of the offshore floating horizontal axis wind turbines (OF-HAWTs) under a certain DOF motion. Therein, Sant et al. [11] conducted an experiment to test the thrust and power variations of an OF-HAWT with a particular wave frequency. Daniel and Tonio [12] used the Blade Element Momentum (BEM), the Actuator Disc Navier-Stocks model, and the Generalized Dynamic Wake model to investigate the loading effects on the OF-HAWTs in surge motion. Tran and Kim [2] employed the conventional BEM approach and the computational fluid dynamics (CFD) method to study the effect of surge motion on the unsteady aerodynamic interference. Jeon et al. [13] investigated the unsteady aerodynamics of an OF-HAWT under the pitch motion of the platform by using the vortex lattice method. Tran and Kim [14] performed the CFD method with the overset mesh technique to study the aerodynamics of an OF-HAWT under the combined effect of pitching and yawing motions. For the OF-VAWTs, Cheng et al. [15] used an aero-hydro-servo-elastic method to analyze the effect of the number of blades on the dynamics, and they found that the aerodynamic loads and structural responses were strongly dependent on the number of blades. Nevertheless, little research focused on the aerodynamics of OF-VAWTs under a certain DOF motion in the past. Therein, the surge motion is one of the main forms of motion [16], which may severely influence the aerodynamic performance of OF-VAWTs. At the same time, understanding the aerodynamics of OF-VAWTs in surge motion can provide some suggestions for the optimization design of the wind turbines. In view of those reasons, the present study will be promoted by this interesting topic.

The Momentum model, the Vortex model, and the Cascade model are the broadly used methods to calculate the aerodynamic forces of the vertical axis wind turbines (VAWTs) [17]. However, they could not capture the detailed flow field information, and the calculated results might show a larger error when compared with the experimental data [17]. In recent decades, the CFD method has been increasingly used to simulate the aerodynamics of the VAWTs due to the higher accuracy. For instance, Wang et al. [18] employed the two-dimension (2D) CFD model to investigate the aerodynamic performance of a VAWT with adaptive blades, and they found that the adaptive blades can improve the turbine's performance. Bianchini et al. [19] studied the impact of virtual incidence on airfoils of Darrieus wind turbines by using the 2D CFD model, and the results obtained by the CFD method are close to the theoretical values. Li et al. [20] predicted the performance and flow field of an H-rotor VAWT by comparing the three-dimensional (3D) CFD model with the experiments, indicating that the 3D CFD simulation is a more precise approach. Cai at al. [21] employed a 3D CFD method with the turbulence model of SST k-ω to calculate a three-bladed VAWT, and the predicted power coefficients fit well with the experimental data. Joo et al. [22] investigated the aerodynamic performance of the H-rotor VAWTs at different solidities and rotating speeds by using the 3D CFD model, and the changing rules of the torque along with solidities and rotating speeds were investigated. Lee and Lim [23] used the 3D RANS model to simulate a three-bladed VAWT, and investigated the impact of pitch angle on the performance. The mentioned studies above all adopted the Reynolds-averaged Navier-Stokes (RANS) turbulence model. In contrast to the RANS model, large eddy simulation (LES) and detached eddy simulation (DES) may offer more precise results [17]. However, the LES method requires a relatively larger amount of computation so that it's rarely used for practical calculation [24].

The Improved Delayed Detached Eddy Simulation (IDDES) is a hybrid method, which combines the SST k-ω based model with the LES approach [25]. It has been employed to solve some kinds of flow problems. Krappel et al. [26] compared the results predicted by the IDDES model with the experimental data by studying a Francis pump turbine flow, showing the details can be resolved by the IDDES. Wang et al. [27] utilized the IDDES and the flamelet model to simulate the hydrogen-fueled supersonic combustion. They found that the IDDES model can capture different scales of turbulent vortices and better deal with turbulent transport processes. Ghasemian et al. [28] performed the IDDES to predict the aerodynamic noise of a HAWT, and the pressure coefficient predicted by the IDDES has a good agreement with the experimental value. The IDDES model can better simulate the turbulence both in mildly separated flow and massively separated flow [25], and has been used in predicting the aerodynamics of VAWTs [29,30].

In the previous studies the aerodynamic performance of the VAWTs is concentrated on the bottom-fixed type. Peng et al. [31] conducted the wind tunnel tests and large eddy simulations to investigate the turbulence effects on the wake characteristics and aerodynamic performance of a VAWT. Li et al. [32] studied the effect of rotor aspect ratio and solidity on a straight-bladed VAWT by using the three-dimensional panel method. Moreover, other topics of the VAWTs are discussed by some researches, for instance, the start-up characteristics of wind turbines with different NACA 4-digit series blade airfoils [33], the influence of the improved airfoil family of the blade on the aerodynamics [34]. In contrast with the studies above, the main purpose of this study is to investigate the aerodynamic performance of an OF-VAWT in periodic surge motion. The schematic diagram of surge motion for an OF-VAWT is shown in Fig. 1. In order to understand the overall performance, the CFD method with the turbulence model of IDDES is employed for the simulations as it can more accurately predict the aerodynamics of VAWTs in the condition of flow separation. Due to the lack of experimental data about the OF-VAWTs, we

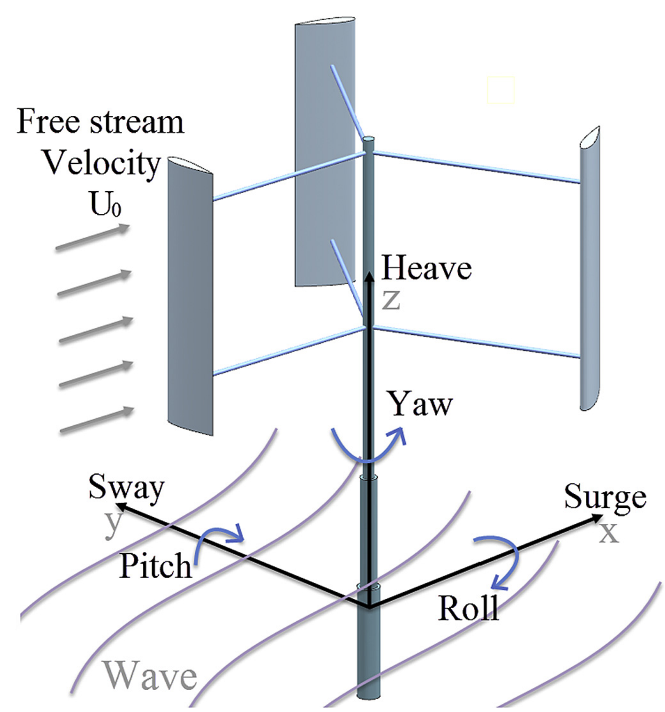

Fig. 1. Diagram of the six-degrees of freedom (6-DOF) for a floating VAWT.

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